4.0 DESIRED CHARACTERISTICS HAZARD WARNING AND AVOIDANCE SYSTEM

4.1 Introduction

Section 2 has introduced some of the operational aspects of the hazard warning and avoidance problems. From the standpoints of both economics and safety, there are basic solutions required. Investigation of the different aspects of the situation leads to an initial conclusion that three broad categories of functional capabilities are required as candidate solutions to the overall low visibility landing situation.

For the purposes of this study, primary emphasis has been placed on the investigation of an airborne solution to the problem. Recognition is made of the fact that alternative, ground-based, solutions to each of the major functional requirements do offer promise. Indeed, additional study and development effort along these lines should be encouraged. However, as the overall spectrum of requirements was analyzed, one immediate, if not rigorous, assumption has been made, that of providing one single integrated system that provides all of the required functions. For this reason, and considering the various phases of flight to which the system must be applied, an airborne self-contained solution was selected to be investigated.

There are three main system functions that need to be provided, each for a variety of reasons. Hereafter in this report, these three functions will be referred to in the following context. The necessity of protecting the aircraft from colliding with high ground or other unusual obstructions to flight, normally during cruising or descending flight, defines a requirement for the capability for High Ground Avoidance (HGA). This requirement manifests itself primarily as a flight safety motivation - to avoid the large percentage of fatal jet accidents directly attributable to hitting high ground.

A combination of flight safety and economic reasons dictate the requirements ascribed to an Independent Approach and Landing Monitor (IALM) whose primary function is to provide acquisition, identification and guidance to a runway approach and landing in visibility conditions including Category IIIC. Intended primarily as a monitor of the performance of the existing ILS equipment in the aircraft, a major system requirement is to reduce the number of accidents categorized as "hit short" or "premature contact with the ground" as identified in Section 2. A secondary but important consideration is the effect on operating economics afforded by the ability of an IALM to reduce delays and

diversions caused by low visibility, particularly if such a system could be certified by the FAA to conditions approaching Category II for airports currently restricted to Category I minima.

Any consideration of Category IIIC operations must include provisions for guiding the aircraft to the ramp under conditions of zero visibility. The system or function which provides this capability has been designated as a Roll-Out and Taxi Aid (ROTA).

Table II-16 summarizes these system functions and their economic and/or safety motiviations.

As a general study ground rule, it can be stated that the requirement for these system capabilities is independent of the existence of an instrument approach system at any given airport. To define the requirement for the system in greater detail, an operationally-oriented study has been performed which defined the:

- Present and probable future operational requirement.
- Information requirements applicable to each system configuration.
- Performance requirements.
- Characteristics of acceptable system(s).

The context in which the study documented herein was performed was:

- The system(s) under consideration is to be an independent source of guidance data for the approach and landing phase of operation.
- It is to provide a terrain warning facility.
- Weather avoidance capability is to be provided in an ultimate integrated system.

  Pilot manipulation requirement is to be minimized in order to assure no significant workload increase during the terminal phase of operation.

  Data display is to be compatible with current systems.
- The objective of the system design is to allow CAT II operation as a minimum, with operation to CAT III weather conditions desirable, including the provision of ROTA (Roll Out and Taxi Aid) capability.

TABLE II-16. FACTORS AFFECTING SYSTEM FUNCTIONAL REQUIREMENTS

Function	Safety Factor	Economic Factor
High Ground Avoidance (HGA)	Prevent accidents caused by striking high ground or other physical obstructions to flight such as buildings, towers, trees, etc., Possible application as proximity warning aid.	Reduce cost of repair or replacement of aircraft due to damage, possible reduction of insurance costs.
Independent Approach and Landing Monitor (IALM)	Prevent accidents caused by premature contact with ground during landing (hit short) or due to misalignment or disorientation with runway.	Reduce aircraft operating cost losses caused by delays or diversions due to low visibility. Reduce cost of repair or replacement of aircraft due to damage, possible reduction of insurance costs. *
Roll-Out and Taxi Aid (ROTA)	Prevent accidents caused by striking ground objects while taxiing (trucks, structures, etc.) or caused by inadvertent leaving of runway or taxiiway.	Reduce aircraft operating cost losses caused by Category IIIC visibility conditions. Reduce cost of repair or replacement of aircraft due to damage while taxiing. *

* In both the IALM and ROTA functions, a primary requirement must be the capability to maintain current IFR landing acceptance rates.

4.2 Operational Environment

The operational environment in which an independent airborne hazard warning and avoidance system must function is discussed in the following paragraphs. In particular, the following aspects of the environment are examined.

- Airports and runway characteristics.
- Aircraft characteristics.
- Cockpit operating procedures.

These data will be utilized in assessing the information and performance requirement for the hazard warning and avoidance system.

4.2.1 Airport Characteristics. - Airport characteristics vary widely from one airport to another. Factors such as the number of runways; how they are configured; their length, width and material and the landing aids which are provided, all form a part of the environment for approach and landing operations. They affect the rates at which aircraft can be handled, the weather in which operations may be conducted and the characteristics which should be required of an additional aid such as the IALM function of the hazard avoidance system.

The current airport environment is typified by the route system of a regional carrier which is shown in Table II-17. This particular route system stretches throughout the northeastern region of the United States. The table was constructed by indicating the best approach aid which a given airport has, and also, those runways on which that aid is available. The runways vary in material content but most are 5000 ft or more in length and 150 ft or more in width. ILS systems are available at many of these airports, but in a number of cases they do not furnish approach capability in conditions corresponding to Category I minima. Category II capability is available at only two of the airports. At the other end of the spectrum one finds a 100'-wide runway shorter than 5000 ft in length, with only an ADF approach capability.

The potential place for the IALM function is clear. It would be valuable if it could help in the further expansion of Category II capability. This was the basis of the economic analysis in Section 3 (this Volume). In addition to that potential, there are additional needs to fully expand ILS capability to the minima of Category I and to develop additional capability for the air carrier to land at airports where no ILS exists. This is the situation as it exists today.

TABLE II-17. TYPICAL REGIONAL AIRLINE SYSTEM - RUNWAYS AND LANDING AIDS

TYPICAL REGIONAL AIRLINE SYSTEM ..... RUNWAYS & LANDING AIDS .....

CITY	DATE/INFO	Rwy	Length	Width	Material	Aid	Vis	DH	
Albany, N.Y.	9/68	19	6000	150	Asphalt	ILS	3/4	300	
Binghamton N.Y.	10/69	34	6300	150	Asphalt	ILS	3/4	250	
Boston, Mass	10/69	4R	10000	150	Bitum-Concr	ILS	1/2	200	
	9/69	33L	10100	150	Bitum-Concr	ILS	1/2	200	
Bridgeport, Conn.	3/68	6	4700	150	Asphalt Concr	VOR			
Buffalo, N.Y.	6/69	5	8100	150	Concrete	ILS	3/4	300	
	1/69	23				ILS	1/2	200	
Burlington, Vt.	10/68	15	7800	150	Bituminous	ILS	1/2	200	
Cleveland, O.	11/68	5R	9000	150	Concrete	ILS	1/2	200	
	11/68	5L	6200	200	Asphalt	ILS	1/2	200	
	9/69	27R	6000	150	Concrete	ILS	3/4	300	
Detroit, Mich.	8/69	3L	10500	200	Concrete	ILS	1/2	200	CAT II RVR 16 (150')
	8/69	21R				ILS	1/2	200	
	8/69	3R	8500	200	Concrete	ILS	1/2	200	
Elmira-Corning, N.Y.	10/69	24	5600	150	Asph Concr	ILS	1	502	
Erie, Pa.	10/69	6	6000	150	Bituminous	ILS	3/4	250	
Glens Falls, N.Y.	12/68	19	5000	150	Macadam	VOR			
Hartford (Windsor Locks), Conn.	9/69	6	9500	220	Bitum-Concr	ILS	1/2	200	
Islip, N.Y.	8/68	6	6000	150	Asphalt	ILS	3/4	250	
Ithica-Cortland, N.Y.	3/69	14	5800	150	Blacktop	VOR			
Jamestown, N.Y.	8/68	25	5300	100	Bituminous	ILS	3/4	300	
Keene, N.H.	6/68	2	5500	150	Bituminous	VOR			
Lebanon(Wht.Rvr.Jct.,Vt.)N.H.	2/68	25	5500	150	Bitum-Concr	VOR			
Manchester, N.H.	9/69	35	7000	150	Bitum-Concr	ILS	1	500	
Massena, N.Y.	1/69	5/23	5000	150	Asphalt	VOR			
Minneapolis, Minn.	4/65	29L	10000	200	Concrete	ILS	3/4	300	
	5/65	4	7250	150	Concrete	ILS	1/2	200	
Montpelier, Vt.	6/68	35	4500	150	Macadam	VOR			
New York, N.Y. (Kennedy)	12/68	4R	8400	150	Concrete	ILS	1/2	200	
	12/68	22L				ILS	1/2	200	
	9/68	31R	10000	150	Concrete	ILS	3/4	300	
(LaGuardia)	9/69	4	7000	150	Asphalt	ILS	3/4	400	
	9/69	22				ILS	1/2	200	
	9/69	13	7000	150	Asphalt	ILS	1	600	
(Newark, N.J.)	9/69	4	7000	200	Asphalt	ILS	1/2	200	
	9/69	22				ILS	1/2	200	
Ogdensburg, N.Y.	5/68	27	5200	150	Bituminous	ADF			
Olean, N.Y.	12/68	22	4700	100	Blacktop	ADF			
Philadelphia, Pa.	6/69	9	9500	150	Bituminous	ILS	1/2	200	
Pittsburgh, Pa.	8/69	27	5500	150	Concrete	ILS	1/2	300	
Plattsburg, N.Y.	7/68	1/10/14	5000	150	Asphalt	VOR			
Poughkeepsie, N.Y.	3/69	24	4000	100	Paved	VOR			
Providence, R.I.	8/68	5R	6500	200	Concrete	ILS	1/2	200	
Rochester, N.Y.	10/69	4	8000	150	Concr & Bit.	ILS	3/4	250	
	10/69	28	5500	150	Bituminous	ILS	1	250	
Rutland, Vt.	1/68	1/19	5000	150	Asphalt	ADF			
Saranac Lake, N.Y.	1/68	5	5000	100	Bituminous	VOR			
Sullivan County, N.Y. (Liberty-Monticello)	8/69	33	6300	150	Asphalt	ADF			
Syracuse, N.Y.	9/69	28	9000	150	Asphalt	ILS	1/2	200	
Utica-Rome, N.Y.	11/68	33	6000	150	Macadam	ILS	1/2	200	
Washington (National), D.C.	9/68	36	6900	200	Asphalt	ILS	1/2	200	CAT II RVR 16 (150')
Watertown, N.Y.	10/69	6	5000	150	Asphalt	VOR			
White Plains, N.Y.	10/69	16	6500	150	Concr & Blacktop	ILS	1/2	200	
Worcester, Mass.	8/69	11	7000	150	Bitum. Concr.	ILS	1	360	

. Airports

Airport characteristics can be expected to change in the future due to increased traffic and the introduction of new types of aircraft. These factors will introduce special problems when designing a new multiple sensor hazard warning system. In particular, the characteristics which will change are:

. More parallel runways will be introduced.

. Special purpose runways and operating areas will be provided for VTOL and STOL aircraft, including helicopters.

  High speed turnoffs fur use at speeds of up to 60 knots will probably be introduced.

. There will be an increase in the simultaneous use of runway facilities.

The problems resulting from these expected changes are:

. The runway identification problem will become more difficult.

. Lateral and vertical guidance accuracy will need improvement.

. The introduction of high speed turnoffs will require more sophisticated roll out and taxi guidance.

. Runway Characteristics

Runway construction practices will continue to be much as they are at present. The combined use of a variety of surface materials is foreseen. Buildup of adjacent hangers, terminals, air-freight and other facilities will continue. There will almost certainly be an increase in the number of multiple land surface traffic arteries which will complicate identification of runways from extreme ranges. In addition to the conglomerate of airfield buildings and surface arteries, the system must be capable of distinguishing among single, crossed multiple, parallel adjacent, parallel staggered, uncrossed multiple and special purpose runways. A problem in some areas (Denver for example) is the location of two airports within two miles of one another.

Runway dimensions can vary as follows:

. Width - 150' to 300'

. Length - 5000' to 15000'

ICAO specified a minimum width of 150 ft which should be used as a design criterion.

Approach paths to the runway are, in general, over terrain which is not level. Ref. (16) specifies the approach terrain model shown in Figure II-1 which should be considered in design of the sensor system.

Other factors in need of definition and for which little data is available relate to typical obstructions in the vicinity of approach trajectories. It is safe to assume that obstructions with heights of up to 1000' can be located on the approach path at the extreme ranges (10 miles). Other obstacles in the form of high ground displaced laterally from the final approach path (from 5 miles in) exist. Approaches at Denver and San Francisco illustrate this problem. The system must locate these obstructions and provide warning data if the threat of impact exists.

4.2.2 Aircraft Characteristics. - The system must be designed ultimately to be used (perhaps in modular form) in a variety of aircraft. The definition given in Ref.(17). for four of these classes are given below:

Class I - Final approach speeds from 60-100 KIAS with descent approach angles from 2-9 degrees.

Class II - Final approach speeds from 101-135 KIAS Approach angles from 2-9 degrees.

Class III - Final approach speed from 136-165 knots Descent angle from 2-6 degrees.

Class IV - Final approach speed from 165 knots upward.

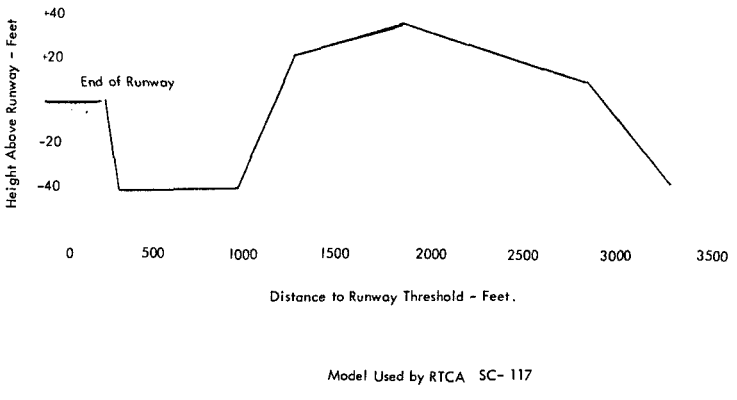

Figure II-1. Standard Elevation Terrain

The study will concentrate on Class III aircraft. Figure II-2 shows the landing approach speeds for a representative set of commercial aircraft.

4.2.3 Operating Procedures used with Present Systems. - In order to provide first hand information concerning current operational ILS techniques, a number of ILS approaches were flown with United Air Lines, with PNSI personnel acting as flight deck observers. Approaches were flown at Chicago (ORD), Reno, San Francisco, Los Angeles and Detroit. The several flight observations were correlated and used to construct an operational scenario and perform the basis for a functional analysis. The particular purpose of this analysis was to identify in general terms the crew functions, workload, and information requirements. For the purpose of this study, an instrument approach to Runway 14R at Chicago's O'Hare Airport was used to construct the model.

- Aircraft Equipment

The aircraft contains the following navigation and related approach guidance equipment.

- Twin VHF Comm/Nav Sets (includes VOR/DME, ILS and communications equipment).

  Twin 4096 ATC Transponders.

  Twin Collins FD109A Flight Director Computers with Attitude Director and Horizontal Situation Displays.

  Autopilot/Flight Director Computer Coupling which can be engaged one channel at a time.

- Approach and Landing Pattern

The operational sequence begins with the aircraft in a holding pattern at Lakewood intersection. The racetrack is executed on an inbound heading of 158°. The aircraft is stepped down in the stack at five minute intervals until it reaches 8,000 ft upon which a radar vectored approach to the ILS is initiated by ATC. The aircraft is simultaneously caused to descend to 4,000 ft and later to 2,200 ft, the altitude required inbound at the outer marker. Normal ATC transponder identification methods are used.

During holding, the aircraft is flown at 230 knots IAS. Final descents are executed using 1500 fpm. During the inbound vectoring, the aircraft is slowed to gear speed and initial approach descent checks are executed. After reaching 2200 ft the prelanding check is completed.

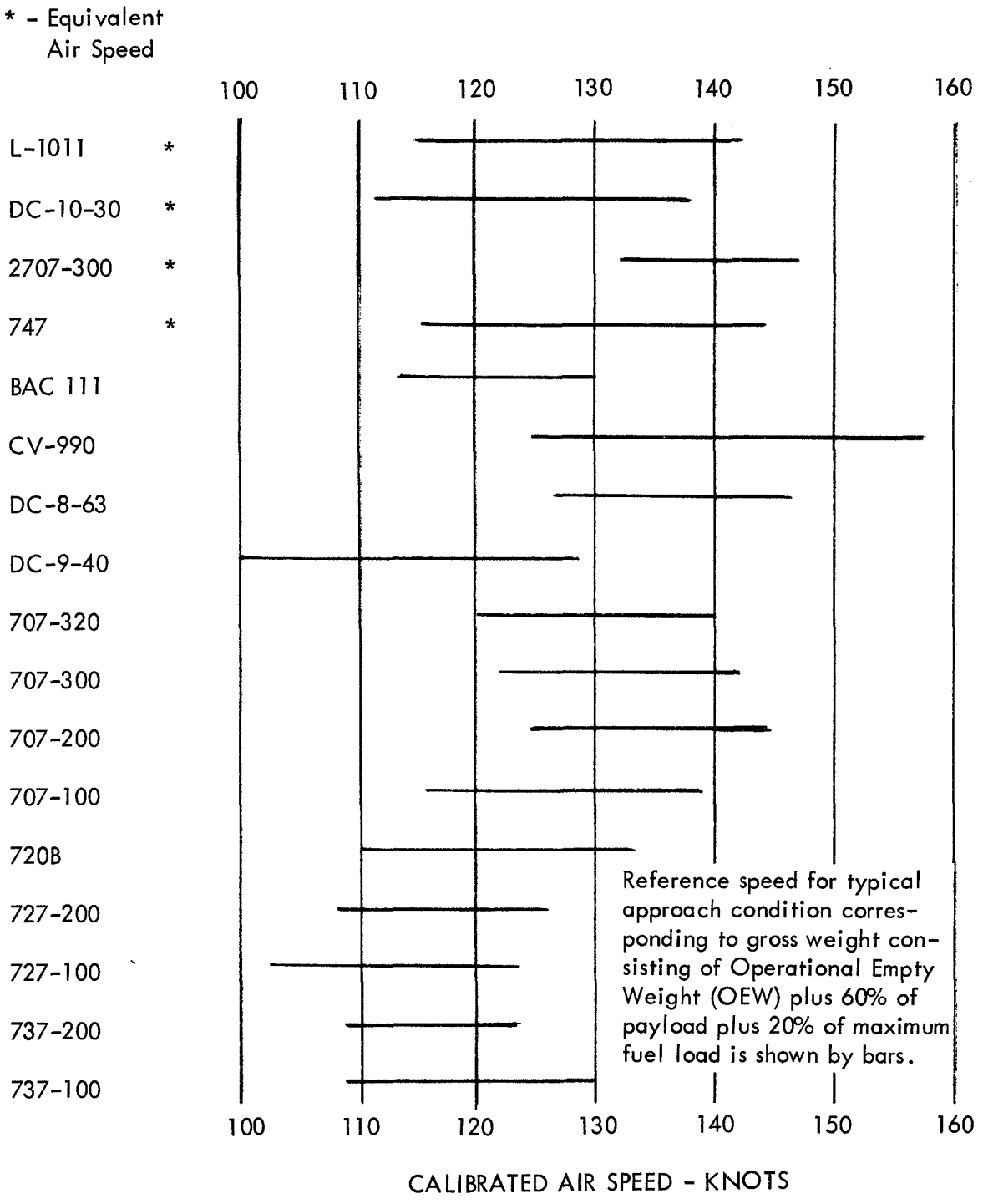

Figure II-2 Reference Speeds for Landing Weights from (OEW + Reserves) to Maximum Landing Weight

The VOR/DME at Northbrook and that at Naperville are used as references during holding. Upon initiating approach, both ILS sets are tuned to IORD and the crew cross checks FD109 indications. An ILS to Runway 14R is executed in coupled mode. If upon reaching minima the aircraft is still in fog, a missed approach sequence is executed. VOR #1 is tuned to DPA (DuPage VOR) for guidance to that point and missed approach guidance is followed.

The approach profiles are shown in Figures II-3 and II-4 together with aircraft speed and other configuration data.

. Timing Sequence

The holding pattern is assumed to start at 31,000 ft. Three steps down the stack are required. Elapsed time in the hold is 15 minutes. Inbound Lakewood to LOM requires approximately 6 minutes. ILS approach from LOM to Missed Approach requires 2.3 minutes.

The total time for approach and landing sequence is approximately 9 minutes. Total time for all equipment set up, landing checks, ATC communications, etc. is 24 minutes. If the holding pattern is not executed, this total time will be significantly reduced.

It will be observed that the flight operation can be divided into four segments. They are:

. Holding.

. Initial descent to 8,000 ft and descent to initial ILS inbound altitude.

Instrument Approach.

Missed Approach segment.

4.3 General System Requirements

4.3.1 Requirements for an Independent Approach and Landing Monitor (IALM). - In order that a pilot be able to safely land an aircraft under conditions of poor visibility, the information he normally obtains by direct visual reference to the ground must be replaced with information supplied from some other source. In general terms, during the actual landing phase, the IALM should be able to center the runway in the field of view of a display at a scale suitable to allow the pilot to positively confirm that what he is seeing is exactly the airfield and runway he wants. Ideally, the system should or could track the desired touch-down point and concurrently show an extrapolation of the existing velocity vector, or

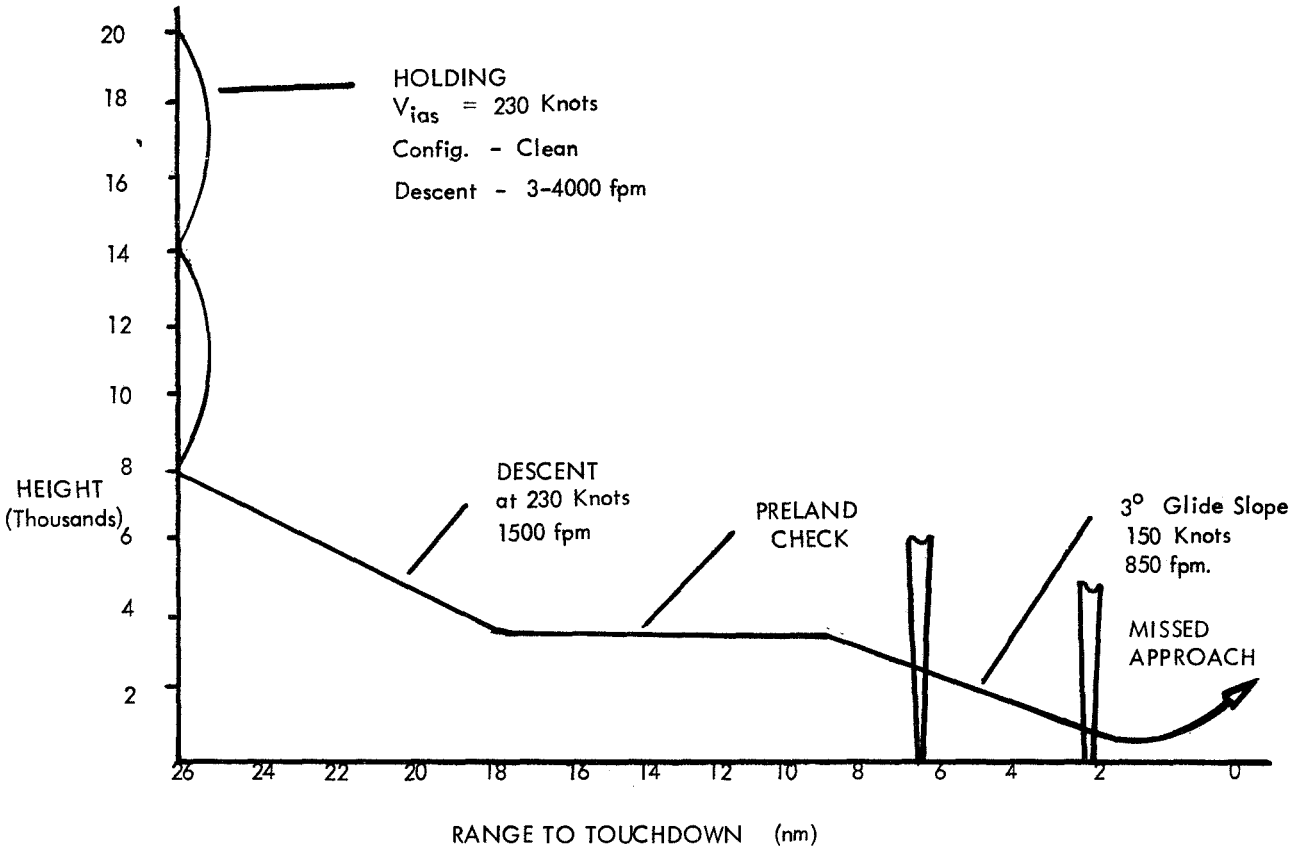

Figure II-3. Vertical Profile

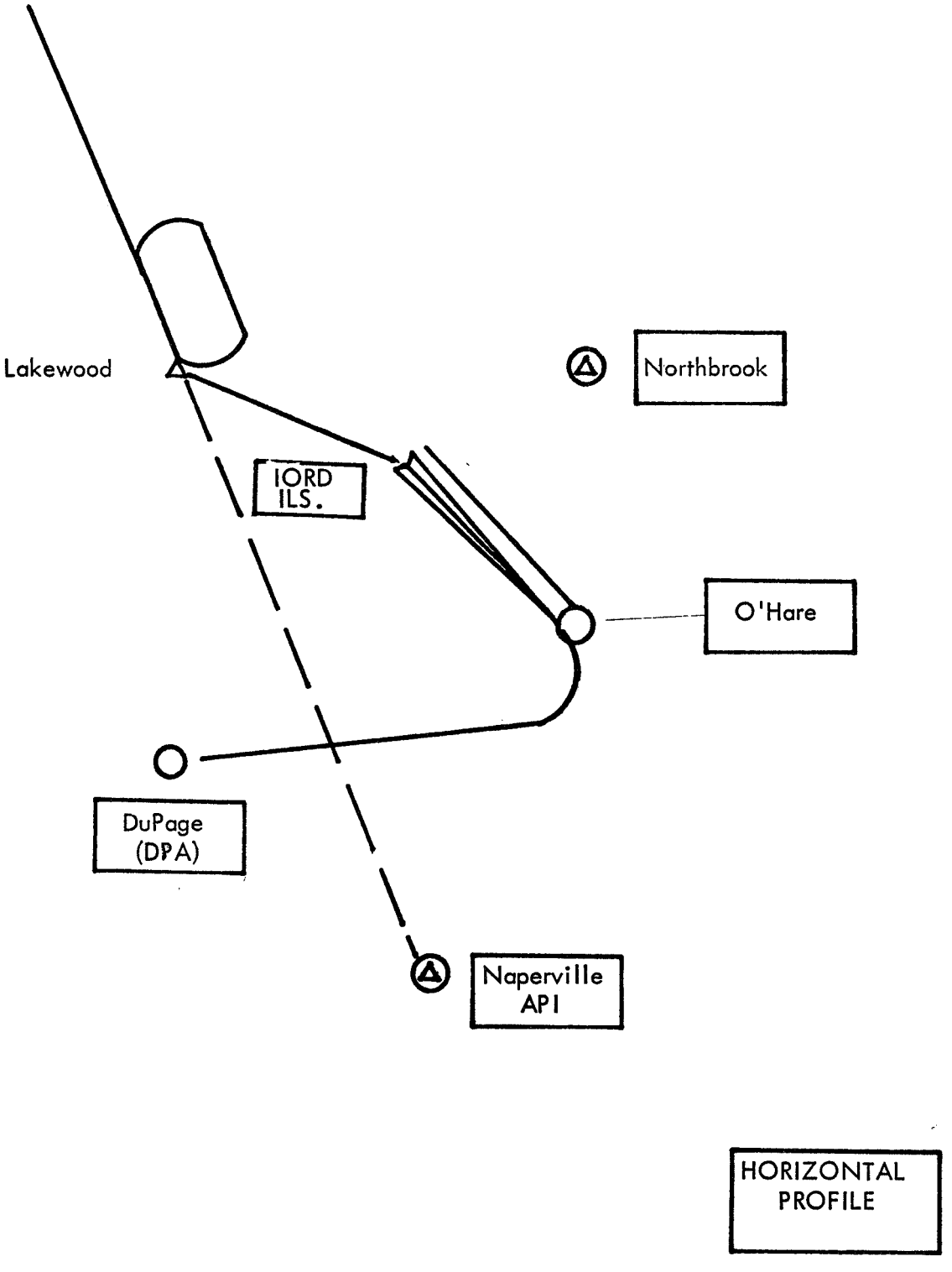

Figure II-4. Horizontal Profile

conversely give the position and attitude of the aircraft with respect to the correct approach path. Another desirable feature of a possible sensor system is the ability to detect other aircraft in the vicinity of the approach path or on the runway.

Possible sensors applicable to this function can be classified into the following two broad types depending upon the type of display they have.

- Sensors providing a pictorial display which is a direct or symbolic representation of what the pilot would see if there were no visibility limitations.

  Sensors providing a director type display showing the distances from the correct approach path in two planes and the range to touchdown.

A pictorial display can be obtained from the following sensor types:

- TV camera with its electron optics chosen to maximize its range in poor visibility conditions.

  Forward looking IR Scanning equipment.

- Ground mapping radar, possibly with reflectors or transponder beacons on the ground to enhance the runway.

- At some later date, the selection of a head-up vs. head-down display concept must be made. At this point in the system development, no conclusions can be drawn concerning relative benefits of either concept.

For a director type display a radar or other suitable sensor is required which measures the range and angular position of a reflector or transponder beacon placed at, or near, the touchdown point.

The suitability of the various sensor types depends upon their performance in poor visibility conditions. Section 6 contains an in-depth analysis of the candidate sensors over a wide range of operating conditions.

Another factor that affects the choice and design of a sensor is the overall system requirements since the sensor is part of a system that includes the pilot and the aircraft.

4.3.2 Requirements for a Roll-Out and Taxi Aid. - After the pilot has landed, he has to roll out, locate the runway exit, and follow the taxiway to the ramp. In poor visibility

conditions on the ground, the taxi speed has to be reduced, and this increases the time it takes for the aircraft to clear the runway. This, in turn, reduces the maximum landing rate at the airport and, at busy airports, aggravates the delays due to poor visibility.

This delay can be reduced by providing the aircraft with a sensor that indicates the center line of the runway, the exit points and the center line of the taxiway leading to the ramp. The greater the distance out in front of the aircraft the sensor can "see", the higher is the safe taxi speed. Another desirable feature of this sensor is the ability to detect obstacles in the path of the aircraft such as airport vehicles and other aircraft. This sensor is called a Roll-Out and Taxi Aid (ROTA).

Possible sensor types are, as for the IALM:

- TV camera with its electro-optics chosen to maximize its range in poor visibility.

  Forward looking IR scanning equipment.

- Ground mapping radar, possibly with reflectors on the ground to enhance the route to be followed.

The performance of possible ROTA sensors is given in Section 6.

4.3.3 Requirements for a High Ground Avoidance Aid. - The pilot must be provided with information which warns him of any high-ground threat or other obstruction to flight in time to allow him to take corrective action. It may be claimed that with the navigation aids now fitted to commercial aircraft, collision with high ground should not occur, either enroute or during the approach and landing phase. The records show that this is not the case. In fact, the number of fatalities from this cause is far greater than those from any other type of accident. It is interesting to note that the majority of these accidents occur during the final approach phase in conditions of poor visibility.

Accidents of this type may be prevented by fitting the aircraft with a sensor which detects ground in the path of the aircraft in sufficient time for the pilot to carry out an avoidance maneuver. Such a sensor is known as a High Ground Avoidance equipment (HGA).

The HGA sensor is typically a radar equipment which measures the range and angular position of the terrain with respect to the flight vector. There are two basic types:

Vertical Profile Type. This sensor determines the profile of the ground along the flight vector by vertical scanning or by interferometer techniques. When high ground intrudes inside a predetermined profile with respect to this flight vector, a warning is given and the pilot climbs to prevent a collision. A turn under these circumstances could

could be dangerous since there is no indication given about the height of the terrain on either side of the flight vector. In its simplest form the sensor measures the range to the terrain along a line which is at a predetermined angle below the flight vector. A warning is given to the pilot when the range is less than a certain value.

Terrain Clearance Plane Type. This sensor scans a horizontal sector in front of the aircraft and terrain above a plane a predetermined distance below the flight vector as shown on a horizontal situation display. A warning is given when high ground along the flight vector could be a hazard to the aircraft. The pilot can decide from the information shown on the display whether to climb or turn in order to get out of danger.

The sensor should be capable of detecting high ground at the maximum required range in all possible weather conditions. If the attenuation in heavy rainfall makes it impossible to detect ground at the maximum required range, the signal back-scattered from the rain should be above the warning threshold. In this circumstance the aircraft would fly above the rain storm. The performance in rain and fog is affected by the wave-length of the radar, and this is discussed in Section 6.

4.4 System Information Requirements

Information requirements for approach and landing, missed approach and terrain avoidance are described below. These requirements are discussed in terms of the services to be provided and the resulting system data requirements. These data are presented in the context of an IALM system which is generating complete guidance data. Several lesser degrees of sophistication are also possible, which would naturally result in less stringent data requirements.

4.4.1 Lateral Guidance - Approach and Landing. - The basic lateral guidance requirements are:

- Definition of the required approach ground track.
- Definition of linear and angular displacement from required ground track.

Definition of distance to go to touchdown.

Roll Command.

The information requirements in terms of current aircraft situation should be available in a sector with an angular dimension of up to 45° from the runway centerline. (Lateral guidance should be available in a sector up to ± 10° and within a range of 10 nautical miles). It is necessary to provide the data shown during approach and up to the ILS reference datum as discussed in Section 5.

The system must also contain Runway Designation (L,R), Runway Length, Runway End Location in XY or Latitude/Longitude Coordinates, and Runway Width.

4.4.2 Vertical Guidance - Approach and Landing. - The vertical guidance information requirements comprise:

- Required Approach Angle and flare pattern (if any).
- Linear and Angular displacement from the required approach path and the rates of departure.
- Definition of required descent rate.
- Runway Elevation.
- Marker Locations.

In addition to these basic data, the system must generate pitch command signals to enable pilot or autopilot control. The pitch command data will be based on displacement and displacement rate (angular or linear from the required glide slope).

4.4.3 Missed Approach Guidance. - Vertical and lateral services must be provided during the missed approach. Of these, vertical guidance is mandatory. The data requirements are:

- Missed approach profile.
- Pitch Command data to missed approach height.
- Obstacle data (height and lateral extent and location).

Other terrain and obstacle avoidance parameters are defined in subsequent paragraphs.

4.4.4 Roll-Out and Taxi Service. - Roll out services should be sufficient to interface with a taxi system if Cat. III operation is feasible. Full taxi services with a self-contained system appear to be difficult to provide since:

Airport runway and taxi patterns are not standardized and therefore to provide guidance with respect to them, using range and azimuth data, would require the storage of a large number of random track coordinates and directions.

- Self-contained sensors in the cluttered airport area will probably not be useful.

Accordingly, it is reasonable as an initial assumption to provide turn off cues after touch-down and obstacle avoidance. Turn off cues can be provided if the on-board sensor measures range from the stop end of the runway.

Requirements are:

- A/C position with respect to runway end point and runway periphery.
- Turn off position with respect to runway end point.
- Turn off track with respect to runway.

4.4.5 Terrain and Obstacle Avoidance Information Requirements. - Terrain and obstacle avoidance data requirements are:

- Range to obstacle or terrain hazard.
- Height of hazard (relative to a/c flight vector).
- Minimum safe altitude above terrain.
- Pitch command to achieve desired clearance.

Aircraft parameters are Configuration, True Airspeed, Placard Limit data (Roll & Pitch Angle limits and maximum acceleration data) and Angle of Attack. Lateral dimensions of the hazard may be provided if turn avoidance is considered. Active pilot participation in the decision process is implicit in such an approach.

4.5 System Performance Requirements

The system performance requirements to acheive both terrain avoidance and Cat. III landing operation are defined below. The pertinent information requirements previously defined are analyzed in detail. The general approach is to define range of variation and subsequently to define accuracies. Data rates are defined on the basis of accuracy and system dynamic requirements.

4.5.1 Range Performance. - A preliminary estimate of the radar detection ranges required for high ground avoidance was obtained by considering aircraft maneuver limits, system time lags and lateral obstacle dimensions. Two cases were considered - obstacle avoidance using a turn maneuver and a pitch maneuver.

The required detection range is made up of two elements: R_d, the minimum range assuming instantaneous aircraft response and R_i, the range increment attributable to system, pilot and aircraft response lags. In the case of a turn maneuver, the value of minimum range is dependent upon the aircraft velocity, permissible load factor during the maneuver, and the desired obstacle clearance or miss distance. The required detection range when using a pitch maneuver is dependent upon the aircraft turn speed, the available climb rate, the vertical extent of the obstacle and the miss distance. Nominal load factors of 1.15 for turn maneuvers and 2.0 for pitch maneuvers were used in this analysis.

The response time lag consists of the three elements of system time lag, aircraft response, and pilot response. System time lag is related to sensor scan rate and the number of detections required prior to determination that an obstacle is present. A typical value of one second was used for this factor. Aircraft response time lag is the time between control application and aircraft response. In the turn case for a large commercial transport, this time lag is typically 1.5 to 2 seconds for establishing a 30° bank angle. For the pitch up case, the response time lag is a function of the time required to establish a flight path angle change and this (assuming no power limitation) is defined by pitch rate. For a load factor of 2, the values of pitch rate are 7.25°/sec at 300 knots and 4.36°/sec at 500 knots. Engine response lag also affects this parameter but it is of the same order of magnitude. Pilot response time is the most unpredictable parameter since it can vary from a minimum of one second to a practical maximum of 15 seconds. This has a substantial effect on detection range requirements. From an analysis of these conditions, the practical design point appears to be pitch avoidance of a 2000' obstacle at 250 knots with a total time lag (τt) of 8 seconds. The minimum detection range requirement then is approximately 30,000' or 5.0 nautical miles. A detection range of somewhat higher order (10 nm) would be desirable.

If a detection range of 5.0 nm is achieved, then this is adequate for worst case turn avoidance at 300 knots ($\tau t = 8$) for an obstacle dimension of 8000' laterally and will allow avoidance of a 3000' obstacle at 500 knots (worst case). Pitch avoidance of a 1300' obstacle at 180 knots is also possible (worst case). With time lags of 8 seconds, obstacles of 6000' can be avoided with turn avoidance at 500 knots and obstacles 1500' high can be avoided with pitch maneuver at 180 knots.

The approach and land case requires detection capability of a higher order. More precisely, it is required that the aircrew be able to establish the system in a normal tracking and monitoring function at least one minute prior to reaching the outer marker whose range is typically 4 nm from touchdown. The time required to execute these functions is

estimated to be two minutes, which for a Class III aircraft results in a detection range requirement of 10 nautical miles. If the detection range achievable is much less than 10 nm, then this implies pilot monitoring of raw sensor data during the final two minutes of the approach which is considered impractical in view of the work loading at that time.

4.5.2 Range Accuracy. - Range accuracy for the terrain avoidance case is set by the magnitude of the safety factor desired. The system can be configured to provide initial warnings at large ranges, hence a low accuracy can be tolerated. (150' will be assumed).

Range accuracy for the landing approach will be established in subsequent analysis.

Height accuracy is set by the clearance height which is to be maintained, which, in turn, determines elevation angle accuracy. A clearance height accuracy of 300 ft at a detection range of 4.8 nm implies an elevation angle accuracy of 0.6°.

4.5.3 Angular Coverage. - The detection range requirements, together with lateral or vertical obstacle dimension, were used to establish the curves shown in Figure II-5. These curves are plots of lateral angle vs. obstacle dimension. The angle (ψ) is determined by assuming that the system must scan an angle whose magnitude is defined by the obstacle dimension and detection range. (The minimum detection range, R_d, was used). From these curves it is seen that if a combined obstacle dimension of 8000' is the maximum, then a lateral angle of $\pm 26^{\circ}$ is adequate. An angular coverage of $\pm 30^{\circ}$ would allow scanning $\pm$ 15,000' laterally when the required minimum detection range is 25,350'.* The vertical coverage required is obtained using the same relationship and adding to this the angle of attack (approximately 10°). This results in vertical coverage requirement of -15°. Coverage in the positive segment is indeterminate but need not be more than $+5^{\circ}$.** (This does not imply that a radar beam angle of $\pm 30^{\circ}$ is required. It implies that data must be provided within these angular limits).

4.5.4 Approach Flight Path . - The approach flight path coverage as specified by Ref. 17, is shown in Figure II-6 (a) & (b).. Class III aircraft will be making use of the 40° approach sector and if segmented linear approach paths are used in horizontal plane, then coverage of $\pm 30^{\circ}$ allows seeing the whole runway width to within 130' of touchdown.

Vertical sector coverage of + 5 and - 15 degrees is required for glide paths of 3°, which is the maximum for Class III aircraft.

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* This would also allow look ahead during turns.

** A stabilized antenna system or a mathematical method for roll angle correction must be provided.

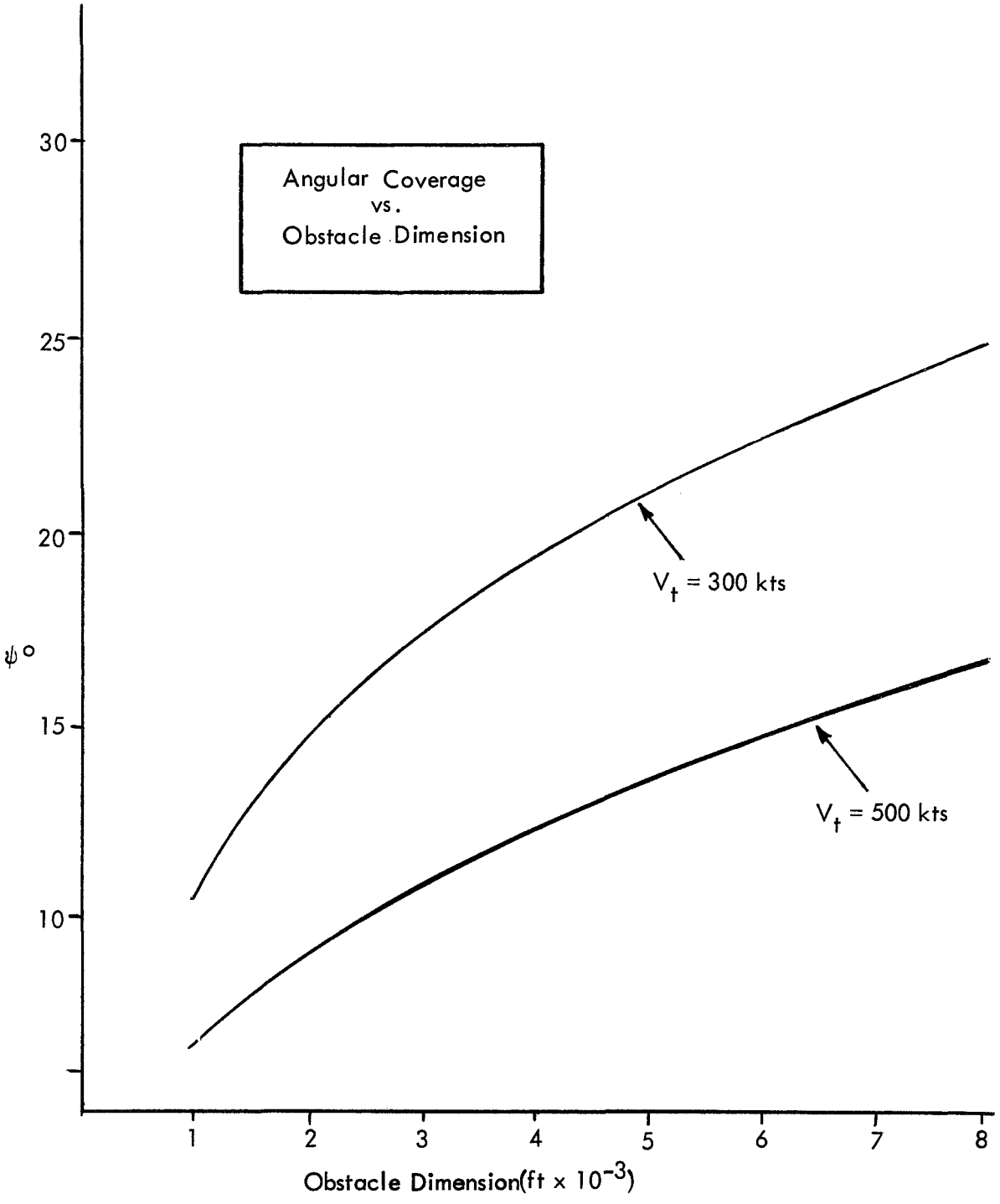
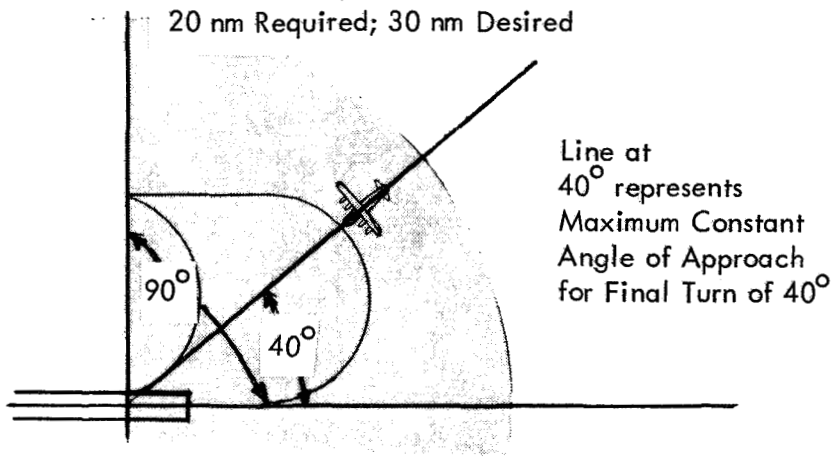
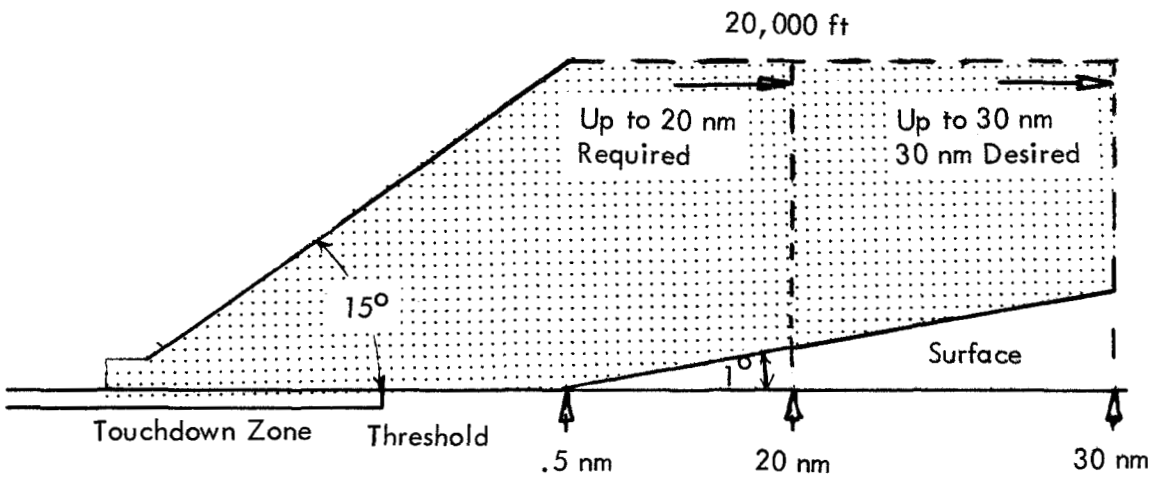


Figure II-5. Angular Coverage vs. Obstacle Dimension



(a) Plan View



(b) Side View

Figure II-6. Approach Flight Path - Plan View and Side View

4.5.5 Accuracy Requirements - Approach and Landing. - The accuracy requirements for glide slope and localizer guidance are discussed below:

. Glide Slope

Guidance accuracy in the vertical plane is determined by the required touchdown accuracy. The geometry of present ILS systems, the performance characteristics of Class III aircraft and typical runway lengths indicate that a touchdown dispersion of ± 750 feet is tolerable (I.E., in the worst case with a 3^{o} glide slope and nominal height at threshold of 50 feet, 1500' of runway can be wasted). The sources of inaccuracy in touchdown are:

. Height Error at Threshold.

. Speed Error at Threshold.

Speed error at threshold will not be considered since, at present, this function is not included in the system. Height error at threshold results from errors in sensing height and in piloting the aircraft. It will be assumed that a piloting error of 12-15 feet occurs. The total allowable error in height contributed by the system is therefore of the order of 10 ft for the nominal conditions considered. It is not considered beneficial to reduce this error significantly in the presence of a piloting error of 12-15 feet. The method of determination of the difference between actual height and required height is to measure slant range and actual height, or to derive height from slant range and radar look angle.

The height above the runway can be obtained from the equation:

$$h = R_s \sin \gamma_l \approx R_s \gamma_l ; \text{ for small } \gamma_l$$

where R_s is the radar slant range

and γ_l is the depression angle of the radar below local horizontal.

Taking differentials:

$$dh = dR_s \gamma_l + R_s d\gamma_l$$

and dividing:

$$\frac{dh}{h} = \frac{dR_s}{R_s} + \frac{d\gamma_l}{\gamma_l}$$

The last equation shows us that the percentage error in height is equal to the sum of the percentage errors in the range and the angle. Applying statistical methods, we can proceed as follows for the conditions:

R_s = 1500 ft

h = 50 ft

γ_I = 3^o

and dh = 10 ft, 3σ value.

$\frac{dh}{h} = \frac{10}{50} = 0.2$ or 20% error.

Then we can allocate 14% error to each of the range and angular errors (3σ). Therefore, for 1500' range, the allowable error is 210 ft and for the 3^o angle, the allowable error is 0.42^o.

At this point in the analysis, the sensor is assumed to be one of three major error sources. Therefore, from a statistical standpoint, the sensor can be attributed with maximum errors which are 60% of the total system error. On this basis, the sensor errors are estimated to be 130 ft in range and 0.25^o in elevation angle.

. Lateral Guidance

The accuracy requirements in the horizontal plane are discussed below. The factors which introduce errors in achieving a given touchdown accuracy are:

. Landing System Accuracy.

. Aircraft Crab Angle.

. Piloting Error.

Aircraft crab angle occurs as a consequence of the necessity to compensate for cross winds during the approach. This angle may reach a magnitude of 10^o with a resultant wheel displacement of 13' for a typical transport (Ref. 18). Piloting error according to FAA AC-120-20 may reach a value of 97' (3σ). A sidestep maneuver may be used to reduce the piloting error. The magnitude of the correction achievable is 20 ft. A total allowable system error of 40 ft will be used. The displacement to left or right of centerline (ΔL) is given by the expression:

$$\Delta L = R_s \text{ Sin } \Delta\psi \approx R_s \Delta\psi$$

where R_s is the slant range and the angle $\Delta\psi$ is the angular difference between the runway heading and the location of the aircraft.

In a manner which is completely analogous to the analysis of the preceding section.

$$\frac{d(\Delta L)}{\Delta L} = \frac{dR_s}{R_s} + \frac{d(\Delta \psi)}{\Delta \psi}$$

The statistical sum of piloting and system errors in 105 ft (3σ). Using this value for ΔL and 40 ft for the value of $d(\Delta L)$, we obtain a percentage error of 38%. This can be budgeted, by statistical means, to 27% errors in each of range and azimuth angle. For a range of 1500 ft and a maximum azimuth error of 3°, the 3σ errors in range and azimuth are 405 ft and 0.81 degrees.

Estimating the magnitude of sensor errors to be 60% of the overall system errors, the sensor errors are 240 ft in range and 0.5° in azimuth.

. Data Rates

The data rates are determined by examination of accuracy requirements and the dynamics of the case being considered. They are discussed below for glide slope and localizer cases. The frequency at which a solution for a particular quantity must be obtained is given by the relationships:

$$\Delta t = \frac{\delta}{R}$$

δ - is required accuracy

R - rate of change of variable

This relationship must be altered somewhat to determine sampling rate if a significant processing delay occurs. The processing delay can, in general, be made insignificant and will, therefore, be ignored in this case.

. Glide Slope Data Rates - The parameters being computed are:

Height Error

Pitch Angle Error

The height error and pitch error, as we have seen are related. The accuracy requirements in each case are:

Height Error – 10 feet

Glide Path Angle Error – 0.4° nominal

The sampling rate is then given by the rate of change of height and the rate of change of pitch angle.

. Height Rates

$$\gamma = 2^{\circ} \quad \frac{dh}{dt} = 9.4 \text{ fps}$$

for V_T = 160 knots

$$\gamma = 3^{\circ} \quad \frac{dh}{dt} = 14.1 \text{ fps}$$

and resultant solution rates for the height channel are:

$\gamma = 2^{\circ}$ - 1 solution every 1.1 seconds

$\gamma = 3^{\circ}$ - 1 solution every 0.71 seconds

based on the necessity of keeping the height error less than 10 feet (solution rate = $\frac{10'}{\text{height rate}}$)

. Lateral Data Rates

Lateral solution rates are set by lateral displacement accuracy, and the rate of change of this parameter.

Lateral displacement rate is set by the velocity and the angle at which the localizer path is being intercepted. This angle can approach 20°.

Therefore, the lateral rate = 268 x Sin 20°

= 91 fps

Lateral Accuracy Requirement is 40'

Then, solution rate required is 2.3 per second.

4.6 Summary

4.6.1 Basic System Functions. - The basic functions to be performed by the system are:

Terrain Warning (High Ground Avoidance)

Generation of Approach and Landing and Missed Approach Guidance Data.

. Roll-Out and Taxi Aid.

In order to perform these tasks the system must process sensor and command data inputs to provide relevant usable outputs to the aircrew. The system must, there, provide both guidance and warning data in each operating mode.* In addition, the system computer can assist the aircrew in sensor selection and control and it can also provide data outputs which will enhance runway acquisition.

. Operating Modes.

The analysis of the operation of the aircraft has shown that at least three major flight operating modes are required in addition to the ground function of roll-out and taxi aid. They are:

. Terrain Warning.

. Approach Mode.

. Missed Approach Mode.

4.6.2 Equipment Constraints. - Each of the three primary system functions, IALM, ROTA, and HGA requires sensors that are essentially forward looking. This dictates an installation somewhere in the nose section of the aircraft, and in the case of a radar sensor, also requires an antenna which must fit within the physical cross section dimensions pertinent to that area of the fuselage. As in any aircraft installation, size and weight are always at a minimum, but there is no particular absolute restriction on either of these parameters for this application.

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* Note that the system configuration descriptions which follow in Section 7 assume that the system is generating command data. The system configurations which will be defined will allow the use of the system in a mode which provides situation "monitoring" only if that is desired.

Considering the continuing requirement and excellent performance of currently available weather radar hardware, this equipment function must be retained. The relatively low cost of components and their proven reliability lend additional emphasis to this goal. Considering the variety of functions and requirements for the overall hazard warning and avoidance system, if each additional function required a separate set of hardware elements, then an extremely demanding installation and cost problem would arise. In the case of the majority of commercial airlines, ARINC installation and interconnection standards are used to specify avionic equipment characteristics. Under these conditions, the overall size and weight of a federated system concept (separate units for separate functions) forces serious consideration of a single multi-function system, perhaps sharing most, if not all, of the basic hardware elements. Further effort therefore should be spent, both in this study, and possibly in future programs, in establishing the feasibility of combining the weather radar function with the IALM, ROTA, and HGA functions into one integrated set of hardware.

The situation regarding the display is even more demanding as regards physical size. Independent of the additional functional capability it can provide, cockpit panel space is at a premium in every aircraft ever built. Careful consideration must be given to the effective combination of software and hardware design techniques for the purpose of providing a multi-sensor multi-function display that occupies the smallest practical, but useful panel space. If possible, some functions of existing or planned instruments should be combined into the IALM, etc. display, preferably eliminating some existing displays.

As will be brought out in considerable detail elsewhere in this report, the economics of any system are of extreme importance, both from a reduction in aircraft operating costs and from the point of view of initial and continued acquisition costs. It therefore is mandatory that minimization of overall system costs be considered in any economic benefit study. This is particularly true for those system configurations aimed at the retrofit market.

Obviously, from the standpoint of reliability, certain well understood system design practices must be followed. A failure in any element of the IALM, ROTA, and HGA systems must not adversely affect safe operation of the primary aircraft systems. At the same time, since the IALM is designed to function as a monitor of the ILS equipment, the IALM equipment must have a reliability at least as good as the equipment being monitored. Provision for system self-test to be performed and displayed must also be an integral part of any proposed set of airborne equipments.

4.6.3 Operational Constraints. - Any system whose functions are as integral to flight safety as are the IALM and HGA must provide operationally significant outputs and/or displays which can be readily utilized by the pilot. Any proposed sensor/processing/display system must provide instant hazard recognition with no required interpretation, particularly considering some of the real-time tasks already being performed by the crew during a low visibility landing situation. The sensor/processing/display concept must

not require specialized training or proficiencies such as radar scope interpretation in order to be useful. If possible, command information should be generated rather than situation data only.

Pilot workload is another serious concern to the system designer. System functions must be organized in such a fashion as to even out the pilot workload peaks and valleys. Extensive operation action, intervention and interpretation are to be avoided as a design criterion.

As mentioned previously, not only must the equipment meet stringent reliability requirements both inherently and through careful system design; it also must contain the capability of detection of misleading signals or information. This self-test ability must include real-time automation annunciation of the existence of any faults within the entire system logical chain. Particularly in the case of the HGA system, it is also important to reduce to a minimum the number of false alarms (or false warnings) related to high ground. These false alarms may arise from either radar scintillations or receiver noise, and although they are not directly hazardous, frequent unnecessary avoidance maneuvers would not be operationally acceptable. Obviously, the system must also be configured so as not to miss or ignore any real or actual hazards.

4.6.4 System Characteristics. - The following Table (II-18) is included as a summary of some of the pertinent characteristics and/or requirements which have been developed in this section. Naturally these characteristics are not necessarily firm, but they do reflect the general character of the performance required of candidate systems.

TABLE II-18. DESIRED SYSTEM CHARACTERISTICS

Glide Slope Angle	2° - 10° *
Maximum Range Requirement	
High Ground Avoidance	5-10 miles
Approach and Landing Monitor	7-10 miles
Azimuth Coverage	$\pm 30^{\circ}$
Azimuth Error	0.8°
Elevation Coverage	$+ 5^{\circ}$ $- 15^{\circ}$
Elevation Error	0.4°
Offset Error at Threshold	$\pm$ 40'
Scan Rate	
Azimuth	2.3 per second
Elevation	1.4 per second
Cross Wind Component	22-28 knots (10° crab angle - Class III aircraft)
Primary System Goal	Independent source of landing approach guidance data. Secondary system goal - high ground avoidance.

* 10° glide slope is an estimate of the requirement for STOL approach procedure requirements.